HIGHLY EFFICIENT DISPOSAL OF CO_2 INTO THE OCEAN BY GAS-LIFT METHOD
(BASIC CHARACTERISTICS OF GLAD SYSTEM)

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Keywords: Carbon dioxide, Gas-lift method, Ocean disposal

INTRODUACTION

7.1 ± 1.1GtC/y of CO_2 was discharged into the atmosphere due to the human activities of energy production and its consumption in 1992 (*1*). Since its discharged rate is quite large in such a matter and CO_2 discharge is continued as long as fossil fuel is consumed, the global warming problem brought by CO_2 is very difficult to solve. Many kind of methods and ideas have been proposed for the problem, however, it is very hard to find out methods to be effective and realized within an early stage.

The mass transfer rate of CO_2 from the atmosphere to the ocean is low (*2*). The ocean has an enough capacity to absorb the whole of CO_2 which is emitted by the consumption of total fossil fuel of 7×10^{12} tonC (*3*). Therefore, CO_2 disposal into the ocean is a reasonable and hopeful option to reduce the global warming. The ocean disposal is not an ultimate technology to avoid the global warming, but emergency measures for the rapid increase of CO_2 concentration in the atmosphere. The ocean disposal is required to be low cost and energy saving as well as possible. The deeper releasing can isolate CO_2 for longer period. Therefore, the deep-sea releasing might be most reliable from a viewpoint of long period isolation of CO_2. However, the liquefaction and transportation of it to the great depth consume a large amount of extra energy and cost (*4*). Thus, we must solve these two contradictory matters; namely reliability and cost.

We propose the GLAD (Gas-Lift Advanced Dissolution) system for CO_2 release into deep-sea as the answer to above-mentioned problems. The GALD system is significantly efficient comparing with previous ideas. In the present paper, the principle of the GLAD system is described and its characteristics is estimated based on recent numerical and experimental results.

SOME PROBLEMS ON PREVIOUS IDEAS FOR CO_2 DISPOSAL

The previous ideas of CO_2 disposal into the ocean are classified into the following categories: the first one is storage of liquid CO_2 on the deep-sea floor deeper than about 3000m. In this case, the surface of the CO_2 pond is expected to be covered by CO_2-hydrate. However, the behavior of CO_2-hydrate in the actual ocean floor is not completely understood (*5*). The second one is direct release of liquid CO_2 into deep water of 1000-3000m in depth (*6*). The released liquid CO_2 should be immediately dissolved and diffused into sea-water to reduce environmental impacts. In these case, the liquefaction of CO_2 and its transportation to great depths consume a large amount of energy and have high cost. Besides, the compressed energy of liquid CO_2 is also disposed in the ocean without work.

The third one is shallow injection of CO_2 gas and gravity current. Haugan and Drange proposed the idea which was direct release of CO_2 gas into the sea-water at the depth of 200-400m and expecting sink of CO_2 enriched solution to deep-sea by the density difference between the solution and ambient sea-water (*7*). Adams et al. improved the CO_2 release system, which was a large vessel fixed on the floor of continental slope at a depth of about 200m (*8*). These ideas are superior to the first and second ones from a viewpoint of energy and cost saving. However, there are uncertain matters from a viewpoint of fluid dynamics in these ideas, such as 1) the upward plume generated by the bubbles, 2) the horizontal turbulence diffusion before the solution reaching at enough depths to be sequestrated for long period and 3) existence of density and/or temperature stratified layer in the ocean (*9*). In addition, considering that biological activities are very high in the area shallower than 200m depth, more deeper release of CO_2 solution without consuming extra energy is quite better. Thus, the uncertainty in the technology and the secondary environmental impact of the previous ideas should be solved simultaneously.

PRINCIPLE OF THE GLAD SYSTEM

The concept of the GLAD system is illustrated in Figure 1 (*9, 10*). The GLAD is an inverse J shape pipeline settled in shallow to deep water. CO_2 gas is injected into the shorter leg (hereafter, called dissolution pipe) of the GLAD at the depth of about 200-400m. Injecting CO_2 bubbles into the dissolution pipe, a gas-liquid bubbly flow is formed and a pumping action is generated by gas-lift effect. The buoyant plume rises in the dissolution pipe, and the bubbles dissolve in sea-water in some ascent. Fresh sew-water flows into the dissolution pipe at its bottom. As a result, the bubble dissolution and the transportation of the CO_2 enriched sea-water to great depth are accelerated by these effects. On the other hand, the longer leg (hereafter, called drain pipe) is used as a transportation and drain pipe for the CO_2 enriched sea-water to the area deeper than 1000m. The density of the solution is larger than that of ambient sea-water. An additional driving force to downward current is promoted by the density difference. Accordingly, the dense solution is released from the end of the drain pipe into deep water very efficiently.

NUMERICAL MODELING AND EXPERIMENTAL APPARATUS

Numerical modeling The numerical models for the gas-liquid two-phase flow in a vertical pipe of inner diameter D were developed (*10*). In the present paper, the outline of the numerical method is described. The basic equations, namely conservation law of mass and momentum, are employed. Defining the density and momentum of the gas-liquid mixture as $\rho=\alpha\rho_G+(1-\alpha)\rho_L$ and $\rho v=\alpha\rho_G v_G+(1-\alpha)\rho_L v_L$ respectively, the equations are as follows:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho v)}{\partial z}=Q_G, \tag{1}$$

$$\frac{\partial(\rho v)}{\partial t}+\frac{\partial\left(\alpha\rho_G v_G^2\right)}{\partial z}+\frac{\partial[1-\alpha]\rho_L v_L^2}{\partial z}=-\frac{\partial p}{\partial z}-\rho g-\frac{4\tau_w}{D}, \tag{2}$$

where α is the void fraction, ρ the density, v the velocity, and the subscripts G and L denote gas and liquid phase, respectively. The vertical direction is represented by z, Q_G is the gas injection rate, p the static pressure, and τ_w the shear friction at the pipe wall, respectively. The void fraction is evaluated by the mass conservation of gas phase

$$\frac{\partial(\alpha\rho_G)}{\partial t}+\frac{\partial(\alpha\rho_G v_G)}{\partial z}=Q_G+\Gamma_G, \tag{3}$$

where Γ_G denotes the gas dissolution rate. In addition, gas equation is employed. As the temperature is assumed to be constant, the energy equation is not needed. To close these equations, the drift flux model which determines the velocity of each phase is applied. Assuming mass transfer coefficient k is constant, Γ_G is evaluated as

$$\Gamma_G=5.24\rho_G k\left(\alpha^2/D^2\Delta_z\right)^{1/3}, \tag{4}$$

where Δ_z is the length of the computational cell (*10*).

The finite difference method is applied to discretized the basic equations. The implicit time marching scheme for density and pressure is adopted to deal with the high compressibility of the gas phase (*11*). The method was applied to a conventional air-lift pump of 200m long, and the numerical results showed reasonable agreement with the experimental data (*12*).

Experimental apparatus The experimental apparatus for the GLAD system is illustrated in Figure 2. Stainless steel pipes ⑨ and ⑩ (100mm in inner diameter and 8190mm in length) are connected to the GLAD dissolution pipe. They allows us to simulate the pressure conditions from the atmospheric to the 200m depth. The dissolution pipe ① is an acrylic pipe of 25mm in inner diameter and 7690mm in total length. At 840mm from the pipe bottom, CO_2 gas is injected by the gas injector ⑦, which is made of 108 19G needles. This injector can form almost uniform bubble diameter for any flow rate of CO_2 gas within the range of the present work.

4 double-optical-fiber probes ② (*13*) shown in Figure 3 are attached on the dissolution pipe in order to measure both of the bubble chord length and the bubble velocity. Each probes can be placed at any radius in the pipe. The optical signals from the probes are detected by the photo-multipliers, and the outputs from the multipliers are converted and recorded in a personal computer. The probability density function obtained by analyzing the probe signal is different from that of the bubble-water two-phase system (*14*), however there is some relationship between these probability density functions. In order to obtain the probability density function of the two-phase system by means of image analysis, a high-speed video camera (200 flames/sec at 20μsec shutter speed) ④ was employed (*15*).

RESULTS AND DISCUSSIONS ON GLAD SYSTEM

Numerical results The numerical results for the same dimensions as those of the experimental apparatus are shown in Figures 4 and 5. To compare the influence of k, two kinds of values, k=1 $\times 10^{-4}$ m/s, 2×10^{-4} m/s, are provided. The initial diameter of the bubbles was given as r_0=3.6$\times$

10^{-3}m (which is obtained by our experiments). CO_2 injection rate was inputted as q_{in} = 0.0164, 0.0328, 0.0656, 0.1312 and 0.2624g/s. Figure 4 compares the effect of CO_2 injection rate on the void fraction at the top of the dissolution pipe (α_{Exit}) and recirculation water velocity (J_L). In the case of k=2$\times 10^{-4}$, the bubbles dissolve completely for q_{in} <10^{-1}g/s, and positive J_L indicates a gas-lift effect takes place. The results fulfills the aim of the GLAD system successfully. In another case, they do not dissolve completely, however, mass flow rate of the CO_2 gas at the top of the dissolution pipe is negligible. Figure 5 shows the vertical profile of the void fraction for above-mentioned q_{in}. Near the gas injection point, the bubbles dissolve very rapidly, and in downstream of this region, the dissolution rate decreases for the both case of k.

Experimental results Comparisons of the experimental results with the numerical ones on both of the void fraction and the recirculation water velocity are shown in Figure 6. In the experiment, the void fraction is determine by taking account of bubble shape given by analyzing the video images. Strictly speaking, the definitions of the void fractions are different. Experimental data mean time void fraction, on the other hand, the numerical ones mean spatial void fraction (*16*). We think, however, the agreement between the experimental and the numerical data is reasonable. In addition, the numerical J_L shows good agreement with the experimental one. In conclusion, the accuracy of our numerical method and modeling is confirmed. In this experiment, a longer pipe is needed for CO_2 to dissolve in water completely. The authors reported, for example, the flow control is effective for complete dissolution of CO_2 bubbles (*9*). The feasibility of the GLAD system has been confirmed by the experiments. Considering the agreement between the experimental results and the numerical ones, the numerical simulation method for a scale-up plant of the GALD system is established.

Model plant and cost estimate In this section, a result of cost estimate for the model plant listed in Table 1 is discussed. (See (*17*) for the detail.) In our estimate, it is assumed that the exhausted rate of CO_2 is 100kg/s and 90 units of the GALD system are employed. The construction charge for both of the GLAD systems and the gas transportation system is about US$ 590 million. If the period of durability is more than 15 years, the operation charge per year, which include the electric power rates, labor costs and the maintenance cost, is about US$ 59 million. Note that the cost for CO_2 capture and separation from the exhausted gas is not included. As a result, the approximate cost of CO_2 disposal into deep-sea form a 1000MW fired power plant by the GALD system is US$ 100 million per year. This corresponds to 1 cent/kWh. The comparison of the cost of the GLAD system with previous ideas is summarized in Table 2.
Still more, the model plant requires only 4% of the generated electricity from the power plant. Note that the cost estimate for CO_2 capture and separation by DOE includes compression to over 100bars. If this compression energy is used effectively for the GLAD system, the cost for it can be rather less than 1 cent/kWh. The GLAD is most competitive to previous methods for deep-sea disposal of CO_2 from a economical point of view.

CONCLUSIONS

The basic characteristics of the GLAD system is examined experimentally. The accuracy of our numerical method is confirmed by the experimental data. Based on these results, the availability of the GLAD system to dispose CO_2 into deep-sea is confirmed from a standpoint of cost and energy. We can conclude the GLAD is the most competitive with previous ideas for CO_2 disposal into the ocean. We are grateful to Dr. Kosugi of Sumitomo Metal Industries, Ltd. for his contribution to the cost estimate and useful discussions.

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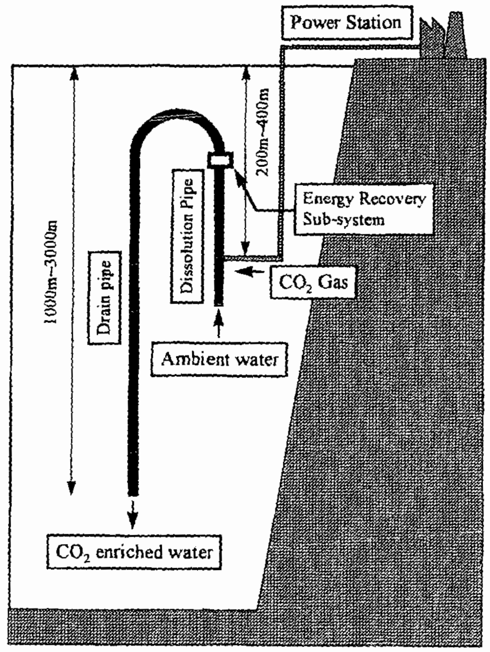
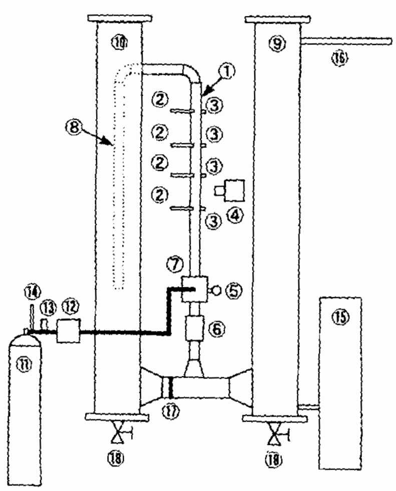


Figure 1. Concept of the GLAD system.
The dissolution and the drain pipes are about 100-200m and about 1000-3000m in length, respectively. CO_2 gas is pumped by a compressor and transported by a pipeline from a fired power plant to the GLAD. In the case that the water recirculation velocity is too high for complete dissolution of the bubbles, a resistance such as a turbine will be equipped near the top of the dissolution pipe. This suggests that excess momentum energy can be recovered. The GLAD system and the disposal method were applied for US and Japanese patent by T. Saito and T. Kajishima (1994, 1995).



① Dissolution pipe
② Double-optical-fiber Probe
③ Pressure transducer
④ High-speed video camera
⑤ Pressure transducer
⑥ Electromagnetic flow meter
⑦ Gas injector
⑧ Drain pipe
⑨ Suction side pressure vessel
⑩ Drain side pressure vessel
⑪ Gas cylinder
⑫ Gas flow meter
⑬ Pressure transducer
⑭ Thermometer
⑮ Accumulator
⑯ Water and pressure supply line
⑰ Orifice
⑱ Drain valve

Figure 2. Outline of the Experimental Apparatus for the GLAD System

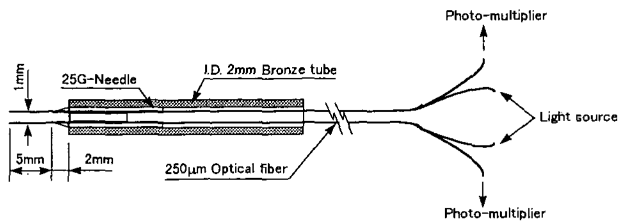


Figure 3. Structure of the double-optical-fiber probe

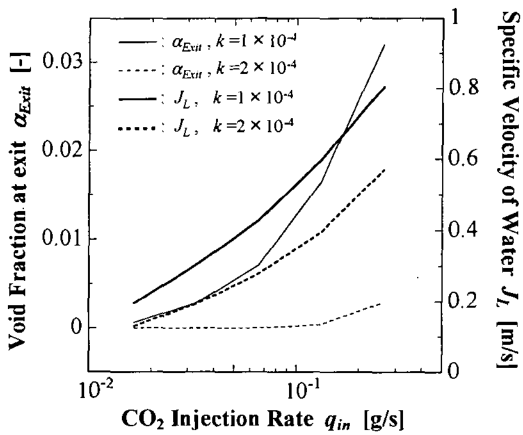


Figure 4. Recirculation velocity of water (J_L) and the Void fraction of CO_2 (α_{Exit}) at the top of the dissolution pipe.

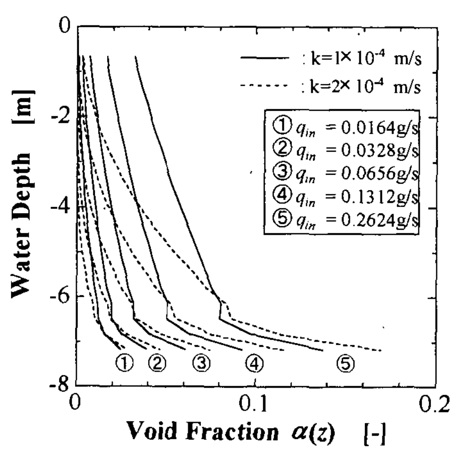


Figure 5. Profile of void fraction of CO_2 gas in the dissolution pipe.

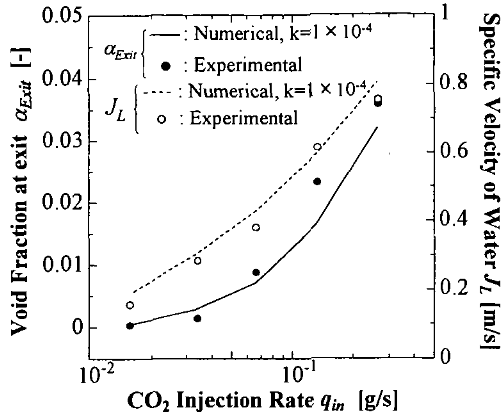


Figure 6. Comparison of the experimental results with the numerical ones.

Table 1. Dimensions of the model plant

GLAD system (fixed by tension-legs)	CO_2 gas transportation system	Power plant (fossil fuel fired)
Steel pipe : I.D.=0.5m, L=300m Inlet depth = 400m Injection depth=390m Drain pipe : I.D.=1.0m, L=10km spirally reinforced FEP	Compressor : 7Mpa, 55m^3/s 412000kW Pipeline : I.D.=0.5m, L=100km	Output power=1000MW CO_2 exhausted rate=100kg/s

Table 2. Comparison of both of previous ideas and the GLAD system

Method	Cost of capture and separation[1),3)] [cent]	Cost of disposal[2)] [cent]
Previous[3)]	1.1 ～ 4.9[3)]	0.6 ～ 6.7[3)]
GLAD	1.1 ～ 4.9[3)]	< 1

1) Includes costs for compression (to over 100bars) and dehydration
2) Includes transportation costs
3) DOE Report, DOE/ER-30194(1993)